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Identifying optimal areas for REDD intervention: East Kalimantan, Indonesia as a case study

Nancy L Harris[1,3], **Silvia Petrova**[1], **Fred Stolle**[2] **and Sandra Brown**[1]

[1] Winrock International, Ecosystem Services Unit, 1621 North Kent Street Suite 1200, Arlington, VA 22209, USA
[2] World Resources Institute, People and Ecosystem Program, 10 G Street NE, Washington, DC 00526, USA

E-mail: nharris@winrock.org

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Abstract

International discussions on reducing emissions from deforestation and degradation (REDD) as a greenhouse gas (GHG) abatement strategy are ongoing under the United Nations Framework Convention on Climate Change (UNFCCC). In the light of these discussions, it behooves countries to be able to determine the relative likelihood of deforestation over a landscape and perform a first order estimation of the potential reduction in GHGs associated with various protection scenarios. This would allow countries to plan their interventions accordingly to maximize carbon benefits, alongside other environmental and socioeconomic benefits, because forest protection programs might be chosen in places where the perceived threat of deforestation is high whereas in reality the threat is low. In this case study, we illustrate a method for creating deforestation threat maps and estimating potential reductions in GHGs from eighteen protected areas in East Kalimantan, Indonesia, that would occur if protection of these areas was well enforced. Results from our analysis indicate that a further 230 720 ha of East Kalimantan's forest area would be lost and approximately 305 million t CO_2 would be emitted from existing protected areas between 2003 and 2013 if the historical rate of deforestation continued unabated. In other words, the emission of 305 million t CO_2 into the atmosphere would be avoided during this period if protection of the existing areas was well enforced. At a price of \$4 per ton of CO_2 (approximate price on the Chicago Climate Exchange in August 2008), this represents an estimated gross income stream of about \$120 million per year. We also identified additional areas with high carbon stocks under high deforestation threat that would be important to protect if the carbon benefits of avoided deforestation activities are to be maximized in this region.

Keywords: deforestation, protected areas, tropical forest, land use change, GEOMOD, REDD

1. Introduction

On a global scale, land use, land use change, and forestry (LULUCF) activities are currently net sources of carbon dioxide to the atmosphere, mainly as a result of deforestation and forest degradation in non-industrialized countries. However, through management, humans have the potential to change the direction and magnitude of the flux of carbon dioxide between the land and atmosphere while simultaneously providing multiple co-benefits to meet environmental and socioeconomic goals of sustainable development.

[3] Author to whom any correspondence should be addressed.

The recognition that LULUCF activities could be both sources and sinks of carbon led to their inclusion in the Kyoto Protocol. However, at present, the Clean Development Mechanism (CDM), related to activities in developing countries, includes only afforestation and reforestation as valid projects in the LULUCF sector (UNFCC 2002a, 2002b). Ongoing discussions under the United Nations Framework Convention on Climate Change (UNFCCC) are now considering reductions in emissions from deforestation and degradation (REDD) in developing countries as an additional LULUCF activity to be allowed post-2012 (Tollefson 2008), a consideration that has generated substantial policy debate among countries worldwide. The outcome of these negotiations will have important implications on the extent to which many tropical developing countries participate in future international agreements to mitigate climate change.

Although deforestation occurs in practically all developing countries (FAO 2006), the actual threat of deforestation in any given country may be high in some places while near zero in others, depending on biophysical, economic and social factors such as site accessibility (e.g., roads, rivers, proximity to towns, elevation), potential timber value, suitability for alternative land uses, presence of community based management, and enforcement (or lack thereof) of applicable laws and regulations related to forestry activities. If a country is to plan where to make REDD interventions to maximize reductions of greenhouse gases and return on investment, it is important to determine the likelihood, or risk, that a given area will be deforested. Identifying forested areas that contain high carbon stocks and that are under high deforestation threat can facilitate policy decisions regarding the placement of new protected areas and the allocation of financial resources towards cost-effective forest protection activities.

Indonesian tropical forests are ranked third for their unique biological richness (behind Brazil and Democratic Republic of Congo) (Global Forest Watch and Forest Watch Indonesia 2002). Over the past 30 yrs, Indonesia exploited its forests to position itself as one of the top major producers of logs, plywood, wood pulp and paper as well as plantation crops such as oil palm, rubber and cacao (Koh and Wilcove 2008, FAOSTAT 2008). For the most part, no sustainable management practices were followed in the execution of this goal and high rates of deforestation have resulted in forests that are both fragmented and degraded. Approximately 84% of Indonesia's total land area of about 193 million ha was forested in the 1950s (Hannibal 1950), while satellite data from 1986–1991 indicate that forested area had decreased to only 69% of the land area (Government of Indonesia/FAO 1996). Today, Indonesia is losing nearly 2 million ha of its forest every year (Forest Watch Indonesia/Global Forest Watch 2002).

Provincial and district planning maps are produced by the Indonesian government approximately every five years to identify specific areas of forest designated for agricultural conversion (i.e., 'planned' deforestation). Unplanned deforestation also occurs in Indonesia as a result of forestlands that are poorly managed and allocated instead to timber industries, plantations and estates, smallholder's tree crop plantations and government-regulated or spontaneous transmigration. Predicting where this unplanned deforestation is likely to occur is much more difficult and the potential impact of these human activities on forest carbon stocks, and thus GHG emissions, varies. For example, forest clearing generally produces the highest quantity of GHG emissions, whereas selective logging may produce lower quantities, depending on the amount of timber removed and the management practices followed (Brown *et al* 2000).

Protected areas are central to conservation strategies designed to safeguard remaining habitats and species from deforestation and other land use change (DeFries *et al* 2005). Although 64% of Kalimantan's land area was allocated to industrial national forest uses from 1967 to 1972, protected areas were delineated or redrawn in 1984 and 1985 and managed by the government to maintain representative ecosystems (MacKinnon *et al* 1996). Since then, however, protected areas have experienced concomitant threats from logging, anthropogenically-induced fires and land use conversion. Therefore, conserving Kalimantan's protected areas requires current information about the nature of the threats that they face (Curran *et al* 2004) and the potential benefits they can provide.

The goal of this effort was to illustrate an approach for identifying key areas that would be important to protect if carbon benefits from REDD activities are to be maximized in a given region. We used a spatial modeling approach to identify specific factors correlated to deforestation trends, predict where future deforestation is likely to occur across large regions, and estimate the potential magnitude of greenhouse gas benefits that could result from forest protection activities if they were well enforced. As such, our approach is intended as a clear and simple decision-making tool for policymakers to evaluate deforestation threat across a landscape and to make decisions about where forest protection activities would be most effective with respect to a REDD mechanism. We tested our approach as a case study in East Kalimantan, Indonesia.

2. Methods

We used a spatial modeling approach to project where future deforestation could occur in East Kalimantan, Indonesia and to assess the relative impacts of protecting forested areas on avoiding CO_2 emissions from deforestation. Data and methods used for the analysis are summarized below.

2.1. Study area

The province of East Kalimantan is located on the island of Borneo between 4° 241′ N and 2° 25′ S latitude and between 113° 44′ E and 119° 00′ E longitude and was the largest province in Indonesia still covered by natural forest in the early 1990s (32% of the total forest in Indonesia was in East Kalimantan, Government of Indonesia/FAO 1996). Elevations range from sea level to 2438 m, with high elevations located

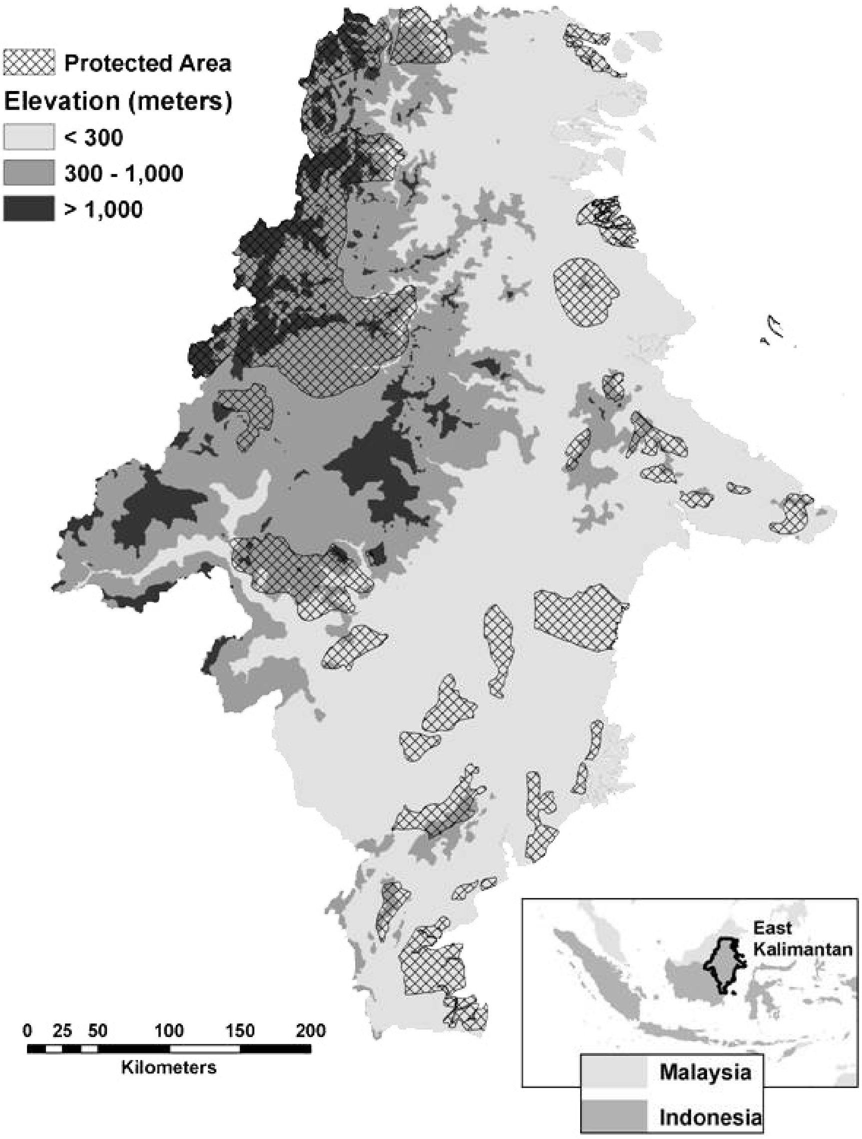

Figure 1. Locations of existing or proposed protected areas in East Kalimantan, Indonesia.

mainly in the northwestern part of the province. Tropical forests in this region are well known for their high biodiversity and range from lowland to montane, with additional areas of peat swamp and mangrove forests. The forests of East Kalimantan contain more than 800 tree species listed as threatened by the International Union for the Conservation of Nature (IUCN) as well as several endangered animal species such as orangutans, proboscis monkeys, sun bears and gibbons (The Nature Conservancy 2006).

According to the World Conservation Monitoring Centre database, eighteen existing and proposed protected areas in East Kalimantan cover approximately 3.7 million ha. Many of these areas (2.3 million ha, or 62%) are at mid- to high elevations (above 300 m) and tend to be inaccessible to logging and other human-induced activities (figure 1). The remaining areas (1.4 million ha, or 38%) are in lowland forests that are more prone to logging operations, shifting cultivation and tree crop plantations.

2.2. Data acquisition

We analyzed the historical rate and location of deforestation in East Kalimantan by comparing land cover maps from various years. The temporal resolution for the analysis was confined by the availability of land cover maps (1997 and 2003). The analysis was performed at 250 m spatial resolution to accommodate the extent of the study area. The following spatial datasets were used (data sources listed in parentheses):

(1) Land cover maps of 1997 and 2003 (Ministry of Forestry, Indonesia)
(2) Roads (Ministry of Forestry, Indonesia)
(3) Rivers (GeoCommunity—GIS Data Depot (2006))
(4) Settlements (South Asian START Regional Center)
(5) Location of sawmills (Ministry of Forestry, Indonesia)
(6) Existing and proposed protected areas (Ministry of Forestry, Indonesia)

Table 1. Area of each land cover class in East Kalimantan according to the Ministry of Forestry land cover classification for 1997 and 2003.

Land cover class	Area (ha)1997	Area (ha) 2003
Forest	12 666 790	10 700 600
Non-Forest	4 970 970	4 866 960
Water and clouds	689 350	2 990 340
Total	18 328 110	18 557 900

(7) Digital elevation model (DEM) (Global Land Cover Facility, University of Maryland (2006))
(8) Forest biomass carbon stocks of Southeast Asia (Brown *et al* 1993).

Although both land cover datasets were obtained from Indonesia's Ministry of Forestry, there were discrepancies in the land cover categories and classified areas. The 1997 land cover map was classified into 18 categories and the total classified area was approximately 230 000 ha less than the total area classified into 24 categories for the 2003 map (table 1). To assure an equal number of classified pixels, all water and cloud pixels were masked out from both maps, as were all classified pixels from one map that did not have corresponding classified pixels in the other map. The resulting land cover categories in both maps were then grouped into one of two broad categories—forest and non-forest. As REDD mechanisms are based on gross forest loss within a country (rather than net loss), pixels that were classified as non-forest in the 1997 map but as forest in the 2003 map were excluded from the analysis. Therefore, this analysis covers deforestation that accrued from the initial area of forest in 1997.

2.3. Spatial modeling

Spatially-explicit models can project the location of future deforestation based on prior knowledge (Brown *et al* 2007). One of the key motives for using spatial modeling within the scope of carbon analyses is that projected future land use change can be associated with forest carbon stocks to estimate corresponding CO_2 emissions. In this work, the spatial model GEOMOD (Hall *et al* 1995, 2000, Pontius *et al* 2001) was used to predict specific locations of deforestation from 2003 to 2013 based on a linear extrapolation of historical deforestation rates between 1997 and 2003. The information needed to run GEOMOD includes reference land cover maps of two categories (forest and non-forest) for an initial (time 1) and subsequent (time 2) time and information on deforested area between these times (derived from the maps). The spatial modeling is performed in two steps. First, the model uses the two category, time 1 land cover reference map along with 'suitability for deforestation' maps (depicting the likelihood of deforestation) and the quantity of deforestation (deforested area (ha) between time 1 and time 2) to simulate another two category land cover map at time 2. The simulated two category land cover map at time 2 is compared to a reference two category land cover map at time 2 to assure proper calibration of GEOMOD. Second, GEOMOD uses the two category land cover map of time 2, suitability for deforestation from the first step and quantity of deforestation in the future (linear extrapolated from the deforestation rate between time 1 and time 2) to predict potential deforestation beyond time 2. Modeling was performed using the capabilities of the Idrisi Andes GIS software package (Eastman 2006). Further details on the GEOMOD model are published in Petrova *et al* (2007).

2.3.1. Rate of deforestation. Within the study area of East Kalimantan, the area of forest cover decreased from approximately 11.1 million ha in 1997 to approximately 9.3 million ha in 2003. The rate of deforestation between 1997 and 2003 was calculated based on the two land cover maps of 1997 and 2003 using the following equation (Puyravaud 2003):

$$\text{Rate} = \left(\frac{1}{t_2 - t_1}\right) \ln\left(\frac{A_2}{A_1}\right) \quad (1)$$

where A_1 is the forest area at the initial time (t_1) according to the land cover map of 1997 and A_2 is the forest area at the final time (t_2) according to the land cover map of 2003. The quantity of forested pixels in future years (2008 and 2013) was estimated using a linear extrapolation of the rate estimated from equation (1) based on the assumption that deforestation would continue at the same rate over this time.

Although fires burned large areas of forest degraded by commercial logging and shifting cultivation in East Kalimantan, it should be noted that the present analysis does not take into consideration the spread of fires; the lack of data on the extent of deforestation caused by fires prevented us from being able to separate deforestation caused by unsustainable timber extraction and clear cutting from that caused by forest fires.

2.3.2. Location of deforestation. Several biophysical and socioeconomic factors have been shown to be correlated to deforestation patterns (Geist and Lambin 2002, Brown *et al* 2007). The first step in predicting the location of deforestation is to create maps of individual factors that may potentially correlate to deforestation trends in the region of interest. Some of the identified factors may be the consequence rather than the cause of deforestation; for example, sawmills are typically distributed over a landscape where demand for timber is high. However, these factors are often correlated to where deforestation is likely to occur or expand even if they do not drive the activity *per se*.

Factor maps were created for East Kalimantan assuming that deforestation decreases with increasing distance from features (roads, rivers, cities, etc) (*heuristic* factor maps) or using prior knowledge (*empirical* factor maps). To create a heuristic factor map, a distance map was created with values representing the Euclidian distance from a target feature (roads, rivers, cities, etc). Values were then scaled from 0 to 255. Elevation and slope maps were also scaled from 0 to 255 and used as heuristic factor maps. To create empirical factor maps, the distance maps were re-classified into 'bins' of 1000 m, the proportion of non-forest area in 1997 for each 'bin' was calculated, and resulting values were scaled from 0 to 255. The slope map was re-classified into 'bins' of 1% and an empirical factor map for slope was created in the same manner. Seven heuristic factor maps (distance from already deforested land, distance from cities, distance from sawmills, distance from rivers, distance from roads, distance from allocated land and elevation) and five empirical factor maps (slope, distance from cities, distance from sawmills, distance from rivers and distance from roads) were created. These 12 factor maps were combined and weighted in 102 unique combinations to create 102 'suitability for change' (SFC) maps. Each SFC map represents the suitability (low to high) of pixels to be deforested based on a weighted-average combination of the factor maps and was used in GEOMOD along with the quantity of non-forest pixels in 2003 to simulate the location of non-forest pixels in 2003.

The model's ability to simulate change accurately from forest to non-forest using each of the SFC maps was validated by comparing the 2003 simulated map to the 2003 reference map and calculating a 'Kappa-for-location' statistic. This statistic measures the model's improvement over what a random selection would achieve (Pontius 2000, 2002). In essence, the Kappa-for-location statistic measures the goodness-of-fit between simulated and reference deforestation trends. A Kappa-for-location statistic was calculated for each of the 102 simulated forest/non-forest maps for 2003. The SFC map used to generate the simulated forest/non-forest map of 2003 that yielded the best Kappa-for-location statistic was used to create a potential land use change (PLUC) map. To create the PLUC map, non-forest pixels in the reference map of 2003 were first masked out of the best SFC map. The PLUC map along with the projected rates of gross deforestation were used in GEOMOD to simulate a future pattern of deforestation in the study area for the 10 yr period 2003–2013.

2.3.3. Estimating potential CO_2 emissions under the reference scenario. The potential CO_2 emissions resulting from the GEOMOD simulation where deforestation in the protected areas was 'allowed', that is, the polygons of protected areas were not constrained during the simulation period, represents a projected business-as-usual, or reference case scenario.

The potential change in carbon stocks, and thus an estimate of emissions, from deforestation was calculated as (IPCC 2006):

$$\Delta C_{\text{conversion}} = \sum_i \{(C_{\text{AFTER}i} - C_{\text{BEFORE}i}) \cdot \Delta A_{\text{TO\_OTHERS}i}\} \tag{2}$$

where: $\Delta C_{\text{conversion}}$ = initial change in carbon stocks on land converted to another land category, t C yr^{-1}; $C_{\text{AFTER}i}$ = carbon stocks on land type i immediately after the conversion, t C ha^{-1}; $C_{\text{BEFORE}i}$ = carbon stocks on land type i before the conversion, t C ha^{-1}; $\Delta A_{\text{TO\_OTHERS}i}$ = area of land use i converted to another land use category in a certain year, ha yr^{-1}; i = type of land use converted to another land use category.

A map of forest carbon stocks (C_{BEFORE} for above-and below-ground biomass for 2003 forested pixels) was created using a map of the spatial distribution of carbon stocks in biomass for the forests of tropical Asia in the year 1980 (Brown *et al* 1993). Given that no updates to this map are presently available, it was assumed that this map of carbon stocks is applicable to the current situation. Non-forest carbon stocks after deforestation (C_{AFTER}) were assumed to be zero and long-term carbon storage in wood products was not considered. The estimated gross change in carbon stocks ($\Delta C_{\text{conversion}}$) was converted to carbon dioxide emissions by multiplying by 44/12 (stoichiometric conversion between CO_2 and C). Potential CO_2 emissions were estimated only for changes in above-and below-ground biomass, not for changes in soil carbon. Non-CO_2 emissions from land clearing with fire were not estimated. (The estimations of potential CO_2 emissions are for illustrative purposes only in this case study and not intended for actual calculation of net carbon emissions.)

3. Results

3.1. Rate of deforestation

Forest area decreased from approximately 11.1 million ha in 1997 to approximately 9.3 million ha in 2003 in East Kalimantan. Using the calculated gross annual deforestation rate for this period (2.9% yr^{-1}), the area of forest projected for 2008 and 2013 shows a continued decrease to 8.1 million and 7.0 million ha, respectively. Non-forest area for the study area was approximately 5.4 million ha in 2003 and increased to 6.7 million in 2008 and 7.8 million ha in 2013. The extrapolated area of non-forest in 2008 and 2013 was used as an input to GEOMOD to predict the location of deforestation in the simulated maps of 2008 and 2013.

3.2. Location of deforestation

Locations of protected areas relative to actual deforested areas between 1997 and 2003 are shown in figure 2(A). Non-forest area within protected areas increased from 390 000 ha in 1997 to 687 000 ha in 2003, suggesting that protection was not well enforced.

Our analysis indicates that the most important factors (heuristically-derived) correlated to deforestation during the reference period of 1997 to 2003 in East Kalimantan were accessibility (distance from already deforested area, distance from cities, distance from sawmills, distance from roads and distance from rivers) and topography (elevation). However, the factor combination of distance from already deforested area, distance from sawmills and elevation yielded the highest Kappa-for-location statistic of approximately 0.7 (table 2). Distance to cities, rivers and roads are correlated to deforestation, but they are likely captured in the single factor of distance to sawmills. None of the three dominant heuristic factor maps selected were able to individually predict the deforestation pattern better than their combination. A suitability for change (SFC) map was created by using a weighted-average combination of the three dominant heuristically-derived factor maps (first row in table 2). According to the SFC map, most of East Kalimantan is very suitable for further deforestation based on past rates and patterns. A simplified deforestation threat map was created by aggregating the pixels in the PLUC map into three equal

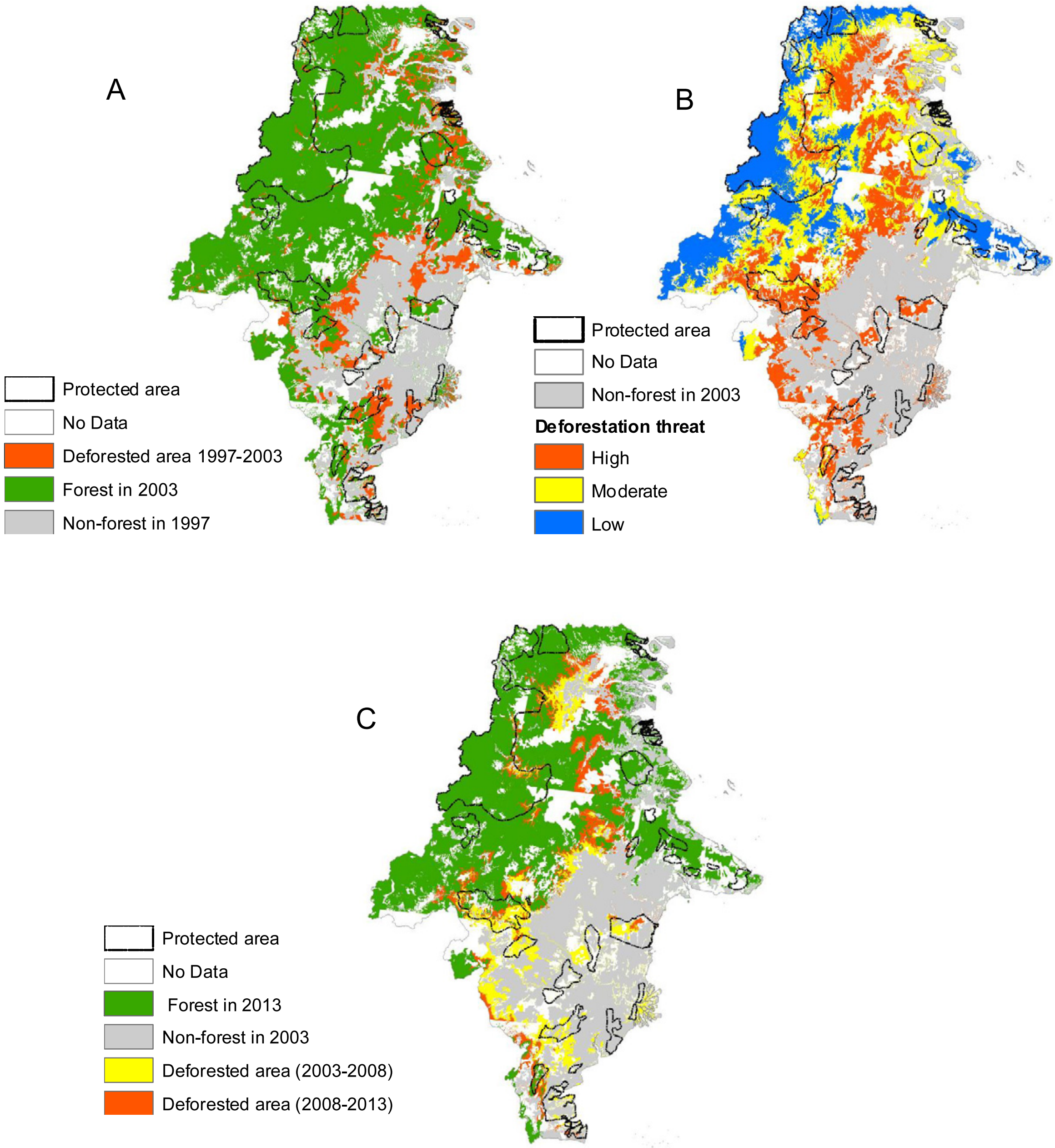

Figure 2. Current state, threats and future state of deforestation in East Kalimantan. (A) Protected areas of East Kalimantan in relation to the area deforested (red) between 1997 and 2003. (B) Threat map of future deforestation, produced from reclassifying the SFC map and masking out already deforested areas. (C) Simulated deforestation in East Kalimantan between 2003 and 2013.

categories to represent high, moderate and low threat classes (figure 2(B)).

The deforestation rate of 2.9% per yr was applied across the entire study area to simulate the quantity of potential future deforestation in 2008 and 2013 by selecting, in descending order, the pixels in the PLUC map with the highest values. Only pixels classified as forest in the 2003 reference map were allowed to be deforested in the model (figure 2(C)).

Under a business-as-usual scenario, most existing and proposed protected areas in East Kalimantan are projected to lose forest cover during the 10 yr simulation period, although the amount varies by protected area (table 3). The total protected forest area (2.4 million ha) in 2003 is projected to decrease to 1.9 million ha in 2013 at a rate of approximately 46 000 ha per year. By 2013, eight existing or proposed protected areas are projected to lose more than 75% of their forest area present in 2003 and six are projected to lose 100% (table 3). Only three protected areas—Gunung Berau, Muara Sebuku and Muara Kayan—are projected to retain all of their forest cover between 2003 and 2013 (table 3 and figure 2(C)).

3.3. CO_2 emissions for the reference scenario

Forest carbon stocks varied from 73 to 383 t C ha^{-1} across East Kalimantan (figure 3(A)), and total forest carbon stocks within

Table 2. Top seven combinations of heuristically-derived factors used to create suitability for change (SFC) maps, and their corresponding Kappa for location statistics.

Kappa for location statistic	Combinations of factor maps used to create suitability maps					
	Accessibility heuristically-derived factor maps					Topography
	Cities	Deforested area	Sawmills	Rivers	Roads	Elevation
0.709		×	×			×
0.707		×	×	×		×
0.703	×	×	×			×
0.700	×	×				×
0.699	×	×	×	×		×
0.695	×	×		×		×
0.693				×	×	×

Table 3. Forest area (ha) for protected areas in East Kalimantan and per cent of projected loss in forest area (ha) for the 10 yr simulated period between 2003 and 2013.

Name	PA total area (ha)	Analyzed area (%)	Forest 2003 (ha)	Forest 2008 (ha)	Forest 2013 (ha)	Projected forest loss (%)
Apar Besar	215 874	74	35 775	6 406	472	99
Apo Kayan NR/BR	89 884	75	65 683	65 683	65 579	0
Batu Kristal	3 470	100	2 538	1 906	1 091	57
Bukit Soeharto	77 630	100	319	6	0	100
Gunung Berau	151 638	94	98 478	98 478	98 478	0
Gunung Lumut	46 337	85	34 267	32 409	23 288	32
Hutan Kapur Sangkulirang	202 621	56	91 086	91 080	86 433	5
Kayan Mentarang	124 341	99	120 724	120 724	119 976	1
Kutai	209 946	84	61 594	17 943	466	99
Long Bangun	333 650	81	258 864	148 653	94 071	64
Muara Kaman Sedulang	80 744	63	5 296	0	0	100
Muara Kayan	73 303	75	21 565	21 565	21 565	0
Muara Sebuku	51 768	74	30 944	30 944	30 944	0
Pantai Samarinda	30 282	79	3 335	6	6	100
Perairan Sungai Mahakam	114 423	53	5 253	0	0	100
Sesulu	125 579	84	32 330	1 146	55	100
Sungai Berambai	73 094	85	43 774	2 660	0	100
Sungai Kayan Sungai Mentarang	1705 679	87	1460 454	1436 743	1372 715	6
Grand Total	3710 262	82	2372 279	2076 354	1915 141	19

protected areas in 2003 were estimated to be approximately 434 million t C. The GEOMOD simulation indicates that when deforestation was allowed to occur within these protected areas, the initial forest carbon stocks decreased by 12% during the first 5 yr period (2003–2008) and by an additional 7% during the second projected 5 yr period (2008–2013).

Combining the change in forest area during the simulation period with estimates of carbon stocks in forest and non-forest resulted in estimates of potential business-as-usual CO_2 emissions for each protected area that would occur in the reference case (table 4). Under a poorly enforced protection program, more than 305 million t CO_2, or about 30 million t CO_2 per year, could be emitted from these eighteen areas of East Kalimantan. Over half of these emissions would originate from just two protected areas, Long Bangun and Sungai Kayan Sungai Mentarang (table 4).

3.4. Identifying new areas for protection activities

The goal of this analysis was to illustrate a clear and simple decision-making tool that allows policymakers to evaluate which areas of forest would be most valuable to protect under a REDD mechanism. This was done by classifying the Brown *et al* (1993) carbon map into four categories—medium (<190 t C ha^{-1}), medium high (190–205 t C ha^{-1}), high (205–230 t C ha^{-1}) and very high (>230 t C ha^{-1}) (figure 3(A))—and combining this four category carbon map with the three category deforestation threat map shown in figure 2(B). The resulting map (figure 3(B)) identifies clearly the forested areas in East Kalimantan with high carbon stocks under high deforestation threat. After overlaying protected areas onto this map, it becomes clear that many of these areas are located within existing and proposed protected areas. According to this analysis, all of the remaining forests in Kutai National Park and Sungai Barambai Nature Reserve are under high deforestation threat and have medium high to very high carbon stocks. Protecting these forests from further deforestation would therefore result in large carbon benefits. The map in figure 3(B) also shows additional forested areas that could generate large carbon benefits if protected in the future. Additional protected forest areas in the southwest region of East Kalimantan (circled area in figure 3(B)) could be established for maximizing the carbon benefits of avoiding further deforestation.

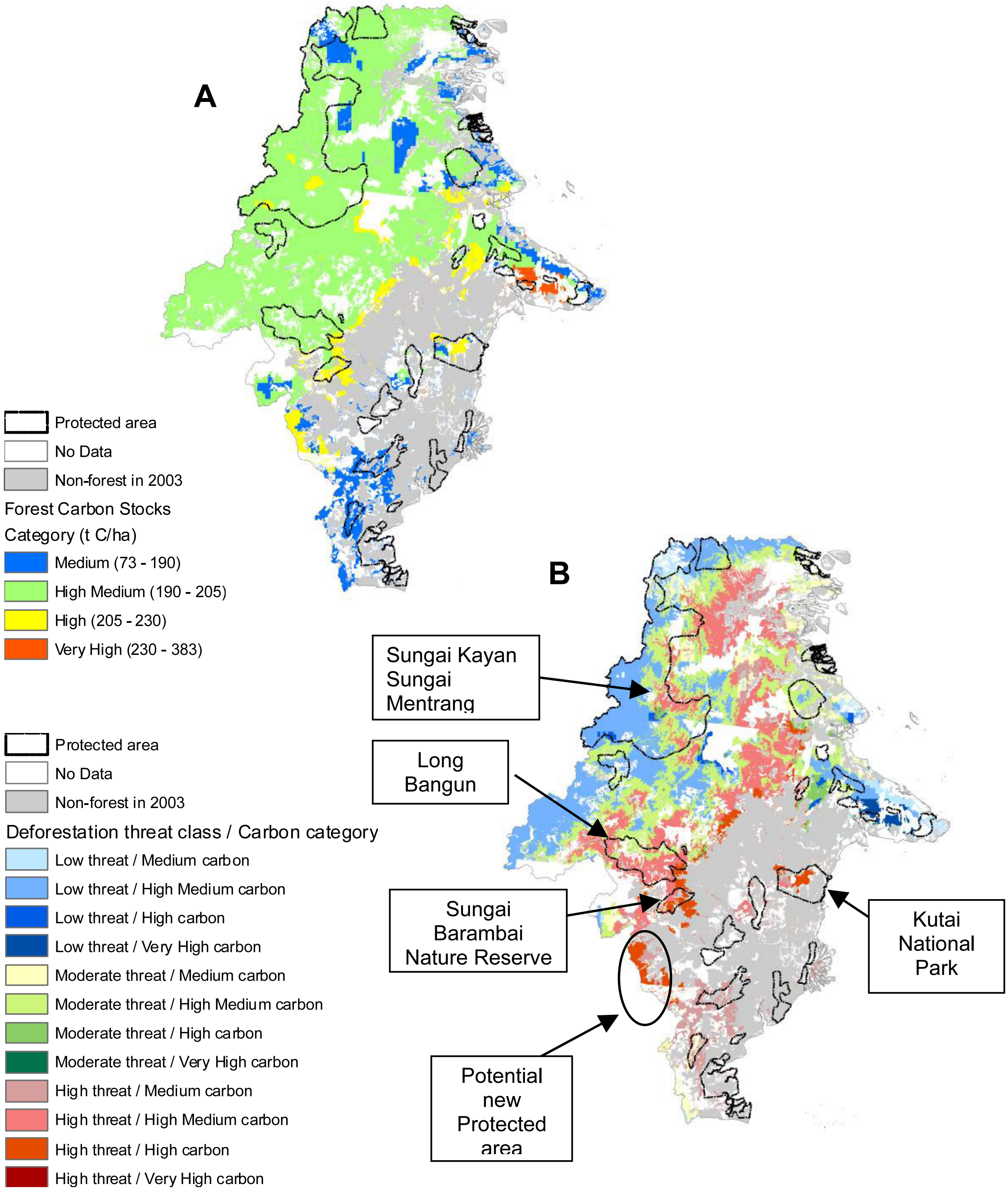

Figure 3. (A) Map of carbon stocks in above- and below-ground biomass pools for the forest area of East Kalimantan in 2003 (from Brown *et al* 1993), illustrating the locations of protected areas. (B) Intersecting forest areas with high deforestation threat between 2003 and 2013 and high carbon stocks can be used to predict potential locations for new protected areas that maximize carbon benefits.

4. Discussion

Gross deforestation in East Kalimantan occurred at a rate of 2.9 percent per year between 1997 and 2003. Our spatial analysis indicates that if this deforestation rate continues unabated across East Kalimantan, a further 457 000 ha of forest, or close to 20% of existing forest, would be lost in protected areas from 2003 to 2013. Under this reference case scenario of non-protection, 305 million t CO_2 would be emitted to the atmosphere. Assuming a price of CO_2 at around US$4 per metric ton over then next 10 yrs (August 2008 price per t CO_2 on the Chicago Climate Exchange; most experts actually expect that the price could climb as high as US$30 per ton CO_2), the opportunity cost of *not* protecting these areas could amount to a gross loss of more than $120 million per year, or approximately $1.2 billion over ten years. In comparison, the Indonesian government's total budget available for all protected areas in Indonesia in 2006 was US$25 million, with

Table 4. Simulated baseline CO_2 emissions per 5 and 10 yr period for protected areas in East Kalimantan, assuming that protection was not rigorously enforced.

Protected area	Average carbon stock (t C ha^{-1})	CO_2e emitted 2003–2008 (t CO_2e)	CO_2e emitted 2008–2013 (t CO_2e)	Total CO_2e emitted 2003–2013 (t CO_2e)
Apar Besar	136	14 612 377	2 952 365	17 564 743
Apo Kayan NR/BR	197	0	75 343	75 343
Batu Kristal	197	456 489	589 447	1 045 935
Bukit Soeharto	106	121 160	2 376	123 536
Gunung Berau	188	0	0	0
Gunung Lumut	175	1 189 500	5 841 507	7 031 007
Hutan Kapur Sangkulirang	197	4 443	3 367 587	3 372 030
Kayan Mentarang	195	0	533 834	533 834
Kutai	198	31 719 966	12 699 568	44 419 534
Long Bangun	187	75 636 892	37 458 751	113 095 644
Muara Kaman Sedulang	171	3 320 572	0	3 320 572
Muara Kayan	104	0	0	0
Muara Sebuku	131	0	0	0
Pantai Samarinda	120	1 467 133	0	1 467 133
Perairan Sungai Mahakam	137	2 641 362	0	2 641 362
Sesulu	155	17 710 015	619 694	18 329 709
Sungai Berambai	209	31 475 247	2 036 716	33 511 964
Sungai Kayan Sungai Mentarang	184	16 011 456	43 236 727	59 248 183
Total		196 366 613	109 413 914	305 780 528

approximately US$5 million allocated for East Kalimantan alone (State Ministry of Environment 2006). Therefore, areas under forest protection are important not only for preserving environmental services, but also for generating potentially large carbon revenue. However, we note that potential carbon benefits were estimated for protected areas as an illustrative example only; individual REDD projects would need to perform much more detailed analyses that included project-specific measures of forest carbon stocks, leakage assessments, calculations of project emissions, etc. Similarly, the potential revenue stream estimated above does not consider factors such as start-up and operating costs of REDD schemes, carbon discount rates or the opportunity costs of forfeiting profits from lucrative land uses such as oil palm.

Rather, our analysis is intended to provide a closer look into one of the most important environmental services of forests: carbon storage. Policymakers and scientists are concerned about deforestation and its negative consequences such as climate change, biodiversity loss, timber supply reduction and soil degradation, and establishing protected areas is a way to preserve environmental and cultural values through reasonable management practices. As global interest grows regarding the carbon benefits associated with forest conservation activities, tropical countries need to be able to identify optimal areas for REDD interventions quickly and easily so that they can take a lead role in protecting forests and the environmental services they provide while potentially generating valuable revenue.

The 1997 and 2003 land cover maps used in this analysis were obtained from Indonesia's Ministry of Forestry (MoF) and represent the most up-to-date official maps available from the Indonesian government. More standardized land cover maps derived from satellite imagery (such as MODIS) are available for more recent years, but cannot be used to validate the deforestation trends simulated in this analysis because the MODIS maps are not directly comparable to those generated by the MoF. Global products have a coarse spatial resolution (1 km) and a generic classification system that has high potential for misclassification when considering specific regions. The MoF maps have a more detailed classification that reflects expert knowledge and the maps were derived from higher resolution imagery (Landsat and others). Although no land cover maps are presently available to validate our 2008 predictions, it should be noted that the purpose of this analysis was to provide policymakers with a method for evaluating the relative threat of land use change over a landscape that can inform decisions on where to site REDD interventions, not to generate precise, pixel-by-pixel predictions of future deforestation.

Spatial models such as GEOMOD can help policymakers to understand where, when and how much forest could be lost to other land uses if current business-as-usual forest management practices (or lack thereof) continue. Many protected areas are proposed or established mainly to conserve biodiversity or cultural values, but spatial modeling of deforestation combined with other spatial data including forest carbon stocks, ranges of endangered or threatened species, areas of cultural value, poverty indicators and key watersheds could be utilized at the planning stage to identify areas where different ecosystem services are maximized and areas where these services overlap. Here, we demonstrated how such an analysis could be implemented by focusing on the question of where to protect forests under high threat of deforestation for the purpose of maximizing potential carbon benefits.

Our results for East Kalimantan are directly relevant to Indonesian policy because they show the potential fate of National Parks and other protected areas and the vital environmental services they provide (including carbon sequestration and biodiversity) if the parks are not well protected and a business-as-usual rate and pattern of deforestation continues. Losses of such large areas of forest in Kutai National Park and Sungai Barambai Nature Reserve are likely to have a large effect on biodiversity and especially on the orangutan population, which is still abundant in Kutai National Park due to its suitable forest habitat. Our analysis gives a clear indication about which existing or proposed protected areas are under threat (table 3) and which areas would have the largest potential carbon benefits if they came under a full protection scenario (table 4). Between 2003 and 2013, deforestation in the two protected areas of Long Bangun and Sungai Kayan Sungai Mentarang (figure 3(B)) is projected to result in over half (56%) of total CO_2 emissions from deforestation in protected areas. Full protection of these areas would therefore reduce greenhouse gas emissions from deforestation substantially in East Kalimantan.

We have shown here a clear, simple decision-making tool that can be used by policymakers for targeting forest protection activities toward forests that are under high threat of deforestation and that would be important to protect if the carbon benefits of these activities are to be maximized. Our analysis can be used by the Ministry of Forestry, environmental advocacy groups and other stakeholders to target forest governance and law enforcement activities. Policy options might include increasing the allocation of funds to certain protected areas, deploying more forest guards, initiating new protection activities in areas identified as having high potential for generating REDD carbon benefits, and initiating educational programs in the vicinity of the National Parks. With the right policies and interventions, the scenarios projected in this analysis can be avoided and policymakers can make informed decisions about REDD interventions going forward.

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